

# Design and Implementation of Sensorless Control for Four-Switch, Three-Phase Brushless DC Motor Drive Based on DSP Technology

A. Halvaei Niasar, A. Vahedi, and H. Moghbelli

**Abstract**—Brushless DC (BLDC) motor is attracting much interest due to its high efficiency, good performance and ease of control for many applications. Moreover, reducing of the drive components is more attractive for low cost applications. This paper presents the design and implementation of a reduced-parts BLDC motor drive using the TMS320LF2407A digital signal processor (DSP). Part reducing is achieved by elimination of three Hall Effect position sensors and reducing the number of power switches. The performance of the proposed reduced parts BLDC motor drive is verified via some simulations. Then, hardware and software details of the system are explored. Finally, an experimental system including a BLDC motor, DSP control board, inverter, and rectifier is set up to validate the theoretical results.

**Index Terms**—BLDC Motor, DSP, sensorless, four-switch inverter.

## I. INTRODUCTION

THE permanent magnet brushless DC motors are increasingly being used in computer, automotive, industrial and household products because of its high torque density, compactness, high efficiency, low maintenance and ease of control [1]. BLDC motor is designed to utilize the trapezoidal back EMF voltages with square wave currents to generate constant torque. BLDC motor is electronically controlled and requires rotor position information for proper commutation of the currents even at fixed-speed application. On the other hand it is important to lower the manufacturing cost of the BLDC motor drive for many applications. Cost reduction of BLDC motor drive is accomplished by two approaches: the topological approach and the control approach. In topology approach, minimum number of switches and eliminating the mechanical sensors are required for the inverter circuit. In the control approach, using high performance processors, algorithms are designed and implemented in conjunction with a reduced component inverter to produce the desired torque characteristics.

On the other hand, with the rapid development in microprocessor technology, the high performance DSP

chip becomes a popular research on digital control for AC drives due to their fast performance, simple circuitry, and on-chip peripherals of a micro-controller into a single chip solution. The DSP controller TMS320LF2407A produced by Texas Instrument, which has the advantages of high speed (MIPS) performance, 2 set (12 outputs) of PWM output, 2 set of QEP (Quadrature Encoder Pulse) input, 16 channels 10-bit A/D converter, General Purpose Input/Output, (GPIO), is very suitable to develop a fully digital controller and a complicated intelligent control algorithm in servo motor drives [2].

This paper presents a low-cost with reduced-parts brushless DC motor drive. To reduce the cost, a four-switch inverter is used. Furthermore, a novel position sensorless control method is developed that three position Hall Effect sensors are eliminated. The validity of developed concept is proved via simulation. Moreover, an experimental setup based on TMS320LF2407A DSP controller is implemented to verify the theoretical results.

## II. ANALYSIS OF SENSORLESS FOUR-SWITCH, THREE-PHASE, BLDC MOTOR DRIVE

### A. Modeling of Three-Phase BLDC Motor

BLDC motor has characteristics like a DC motor, whereas it is controlled the same as AC motors. Fig. 1 shows trapezoidal back-EMF, current profiles, and Hall sensor signals of the three-phase BLDC motor. One electrical cycle of the motor is divided to six  $60^\circ$  modes that at each mode, only two phases are conducting the current. In ideal case, the current profiles are regulated as quasi-square waveforms. The typical mathematical model of a three-phase BLDC motor is described by the following equations.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where  $R$ ,  $L_s$ ,  $M$  are the resistance, inductance and mutual inductance of the stator and  $v_x$ ,  $i_x$  and  $e_x$  are phase voltage, back EMF voltage and phase current of the stator respectively [1]. Electromagnetic torque is expressed as

$$T_e = \frac{Z_p}{2 \cdot \omega_e} (e_a i_a + e_b i_b + e_c i_c) \quad (2)$$

where  $\omega_e$  is the electrical speed of the rotor and  $Z_p$  is the number of magnetic poles.

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A. Halvaei Niasar is with the Department of Electrical Engineering, University of Kashan, Kashan, I. R. Iran (e-mail: halvaei@kashanu.ac.ir).

A. Vahedi is with the Department of Electrical Engineering Iran University of Science and Technology, Tehran, I. R. Iran (e-mail: avahedi@iust.ac.ir).

H. Moghbelli is with the Isfahan University of Technology, Isfahan, Iran. He is currently a visiting Assistant Professor at Department of Science & Mathematics, Texas A&M University at Qatar, Doha, Qatar (e-mail: hassan.moghbelli@qatar.tamu.edu).

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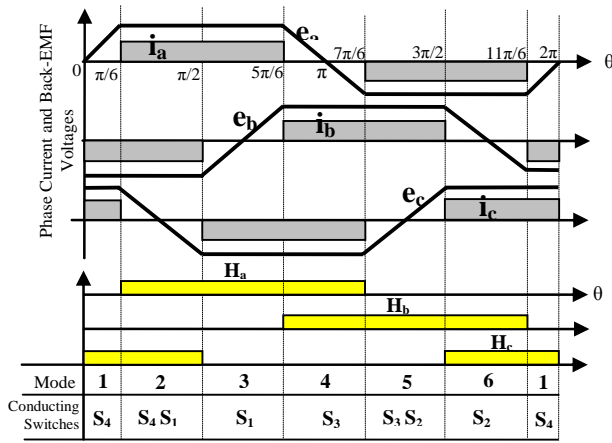


Fig. 1. Phase current and voltage waveforms of a BLDC motor.

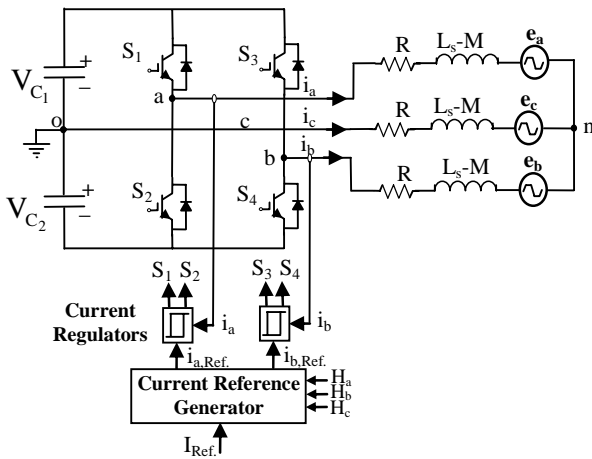


Fig. 2. Phase current and voltage waveforms in a BLDC motor.

**B. Four-Switch Inverter, Three-Phase BLDC Motor Drive**

A BLDC motor needs quasi square current waveforms in order to develop the maximum and constant torque as shown in Fig. 1. Moreover, the phase currents must be synchronized with phase back EMF voltage of a particular phase. Also, at every mode only two phases are conducting and another phase is inactive. However, in the four-switch inverter, the generation of 120° conducting current profiles is inherently difficult due to its limited voltage vectors. Hence, in order to use four-switch inverter topology for the three-phase BLDC motor, direct phase current (DPC) control method is employed [3]. Fig. 2 shows the overall system configuration of a four-switch, three-phase inverter (FSTPI) BLDC motor drive using DPC method. In this method the currents of phases A and B in modes 2 and 5 are controlled independently. Therefore, the current profiles are as same as the currents of a conventional six-switch inverter BLDC motor drive.

**C. Sensorless Control of Four-Switch BLDC Motor Drive**

Sensorless control of BLDC motor has been a research topic for the last two decades. The main methods published in literature can be classified in five categories as [4].

(1) Back EMF sensing techniques (2) Flux estimation method (3) stator inductance variations method (4) observers and classic control techniques and (5) using the special functions of motor variables. The sensorless

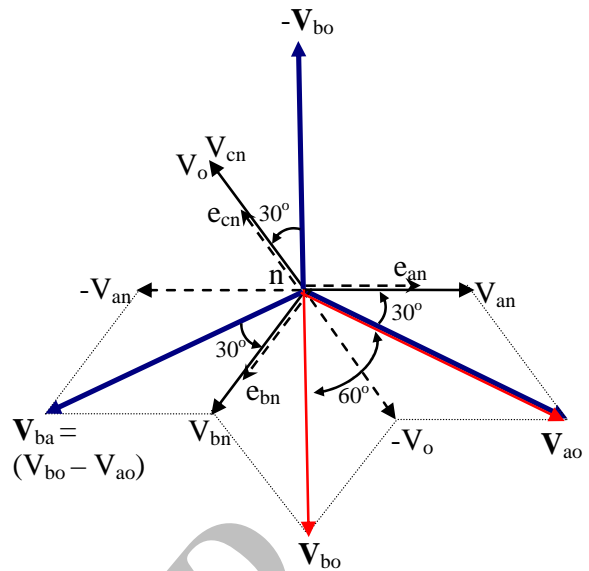


Fig. 3. Phasor diagram of the stator voltages in a four-switch inverter, BLDC motor drive.

techniques that utilize the back EMF voltage of the open-phase are more attractive due to its simplicity and ease of implementation especially for low cost applications.

There are many researches that have utilized the back EMF voltage or terminal voltages and based on the detection of zero crossing points. But most of them have been developed for conventional six-switch BLDC motor drive and actually, there are not any considerable researches for sensorless control of four-switch BLDC motor drive. Lately, in Ref. [5], from two equal points of terminal voltages  $V_{ao}$  and  $V_{bo}$ , two commutation instants are detected. Other four commutation points are detected via interpolation. Accumulation error in this method may cause position error especially in transients. Therefore, a novel method based on detection of zero crossing points of phase back EMF voltage was developed [6]. Three error functions (EFs) were defined so that their zero crossing points are coincide to zero crossing points of the phase back-EMF voltages. The commutation instants are exactly 30° after zero crossing points of error functions. However, creation a 30° delay is the lack of this method that results some position estimation error. Therefore, a novel position sensorless method based on line voltages of BLDC motor is presented and its feasibility is confirmed via simulation and experimental results.

In a four-switch inverter topology, terminal voltages  $V_{ao}$  and  $V_{bo}$  are oriented 60° together as shown in Fig. 3. It results  $V_{ao}$  and  $-V_{bo}$  are 30° phase lag respect to  $e_{an}$  and  $e_{cn}$  respectively. Moreover,  $V_{ba}$  voltage (or  $V_{bo} - V_{ao}$ ) vector has 30° delay respect to  $e_{bn}$ . It means that the zero crossing points of  $V_{ao}$  and  $-V_{bo}$  can be used to commutate the current in phase A and C, and also, while two voltages  $V_{bo}$  and  $V_{ao}$  become equal, two commutation instants of phase B may be detected.

Implementation of the proposed method is easier than other methods even than ones based on back EMF voltages, because there is no need to any phase delay. Moreover, instead of detecting the motor terminal to neutral voltage, that is prevalent in other sensorless methods of BLDC motor drives, the estimated

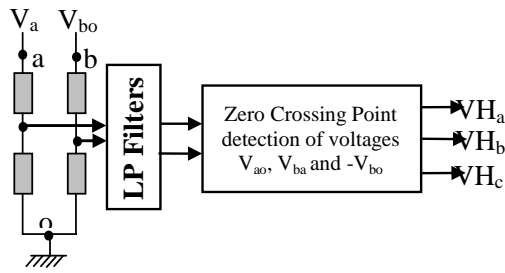


Fig. 4. Estimation of virtual Hall effect sensors using the proposed sensorless method.

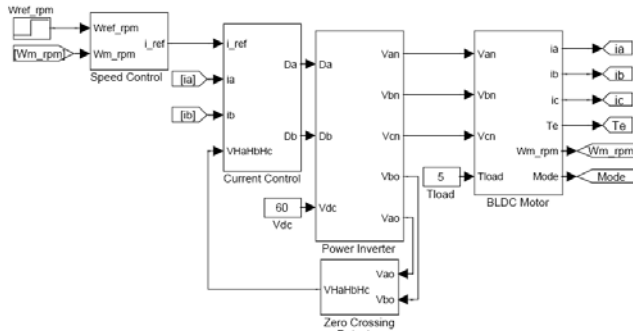


Fig. 5. Simulation diagram of the sensorless-controlled, four-switch BLDC motor drive in MATLAB/Simulink.

TABLE I  
BLDC MOTOR PARAMETERS

Symbol	Value	Symbol	Value
$P_n$	425 [W]	$Z_p$	16 [pole]
$T_n$	12 [N.m]	$\omega_n$	350 [rpm]
$I_n$	10 [A]	VDC-bus	60 [V]
$R$	0.64 [ $\Omega$ ]	$J$	5e-4 [Kg. m <sup>2</sup> ]
$L_s$	1.0 [mH]	$M$	0.25 [mH]
$K_t$	1.194 [N.m/A]	$K_e$	0.0667 [V/rpm]

commutation signals are extracted directly from the average line to line voltages. Filtering of terminal voltages  $V_{ao}$  and  $V_{bo}$  is essential issue in this method. Terminal voltages are filtered via two low pass filters for following reasons; (1) elimination of switching noises (2) calculation of average terminal voltages. However, low pass filters may cause little delay like to most of sensorless methods that is negligible. Fig. 4 shows the measuring and filtering of phases A and B terminal voltages corresponding to the middle point of DC-bus. Zero crossing point detection results virtual hall signals and can be carried out in hardware or software. Using DSP controller with embedded A/D inputs eliminates using extra hardware to detect zero crossing points and it can be implemented in software.

#### D. Simulation of the Novel Sensorless Control Method for Four-Switch Inverter, BLDC Motor Drive

In this section, the validity of proposed sensorless techniques is proved via some simulations. Fig. 5 shows the overall block diagram of the sensorless-controlled, four-switch inverter BLDC motor drive in Simulink. BLDC motor is a high-torque; low-speed motor with 16 poles that its parameters are given in Table I. Speed control block creates the current reference. In current control block using direct phase current control method, the phase currents are regulated and duty cycles of power switches are generated.

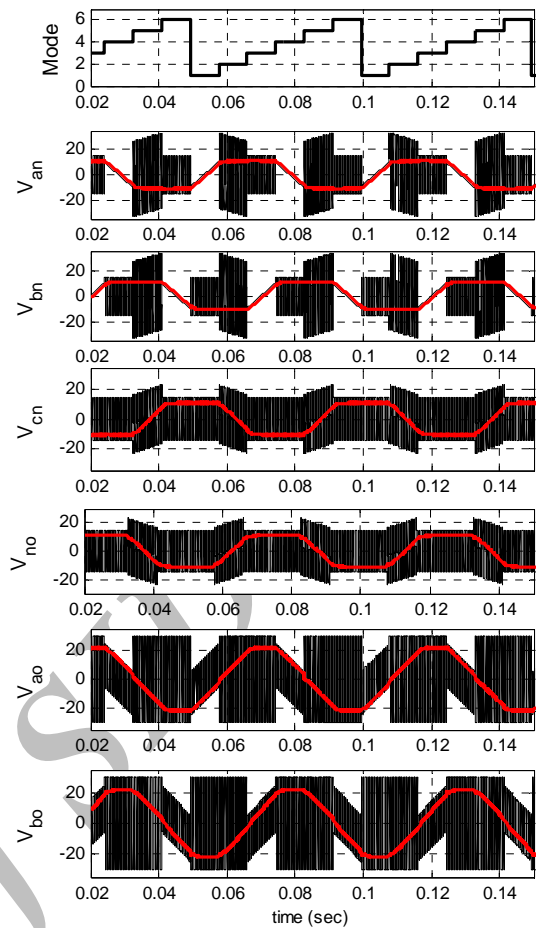


Fig. 6. Voltage waveforms of a four-switch inverter, BLDC motor drive via DPC control method at 150 rpm.

In power inverter block, proper phase voltages are generated and applied to BLDC motor. In zero crossing detector block, the zero crossing points of the three line voltages are detected and then virtual Hall signals are made to identify the commutation instants as shown in Fig. 5(b). Two second-order Butterworth low pass filters with pass-band frequency of 700 rad/sec are used to eliminate high frequency components of PWM voltages. Fig. 6 shows the phase and terminal voltages and their corresponding filtered signals of four-switch inverter BLDC motor drive at speed 150 rpm. Fig. 7 shows three line voltages, phase currents and virtual Hall sensors waveforms at the speed 150 rpm (1200 electrical rpm) where the current waveforms are in rectangular shape.

### III. DSP IMPLEMENTATION OF THE DEVELOPED REDUCED-PARTS BLDC MOTOR DRIVE

In this section, implementation of the developed sensorless control method for four-switch BLDC motor drive using TMS320LF2407A DSP including DPC control method by using virtual hall sensors signals are explored in details.

#### A. System Hardware Structure

Fig. 8 shows a schematic of the hardware system that composes of the following parts: DSP board, switch drive circuits, current sensing circuits, zero crossing detection circuit, IGBT modules, BLDC motor, and DC-link part including rectifier, capacitor and brake resistor. As following, the main parts are described briefly.

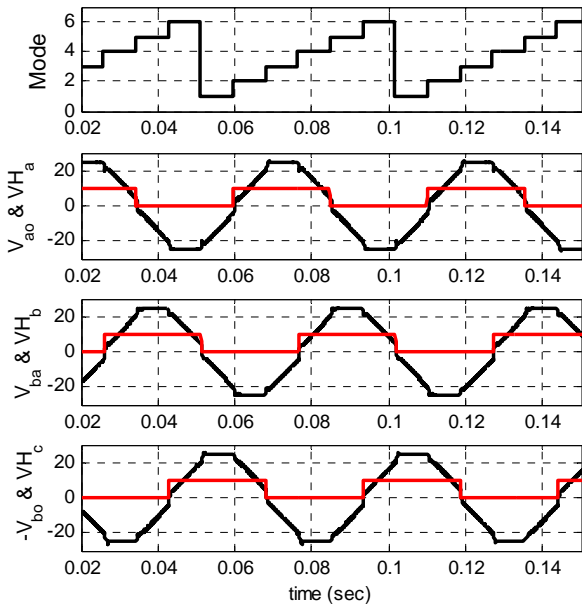


Fig. 7. Sensorless control based on zero crossing of line voltages at 150 rpm, (a) Line voltages waveforms and corresponding virtual Hall sensor signals and (b) Phases current waveforms.

1) DSP Controller

An eZdsp board of TMS320LF2407A DSP acts as controller to control the whole of the system. It reads the current and position feedback, implements the torque control algorithm and finally generates the gate signals. DSP can take the command speed/torque/current from remote via its CAN, SPI, SCI ports or from an external potentiometer through ADC units. Voltage and current signals after pre-conditioning circuits come into ADC modules to be converted to digital signals. At the end of each cycle, DSP generates four PWM signals, and sends to opto-isolated switch drivers. The switch drivers isolate and amplify the DSP commands and send to power module.

2) Switch Driver Circuit

The output pulses from TMS320LF2407A DSP are not capable of directly driving the IGBTs of higher ratings. Hence device drivers HCPL A316J are used. Four driver circuits are used to drive the IGBTs. Fig. 9 shows the schematic of each A316J drive board.

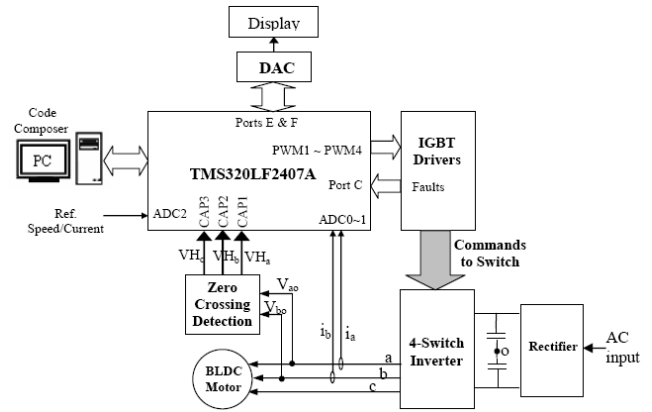


Fig. 8. Hardware structure of four-switch, BLDC motor drive base on TMS320LF2407A DSP.

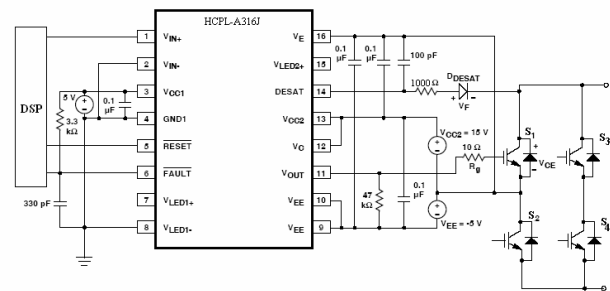


Fig. 9. Circuit schematic of HCPL-316 switch driver.

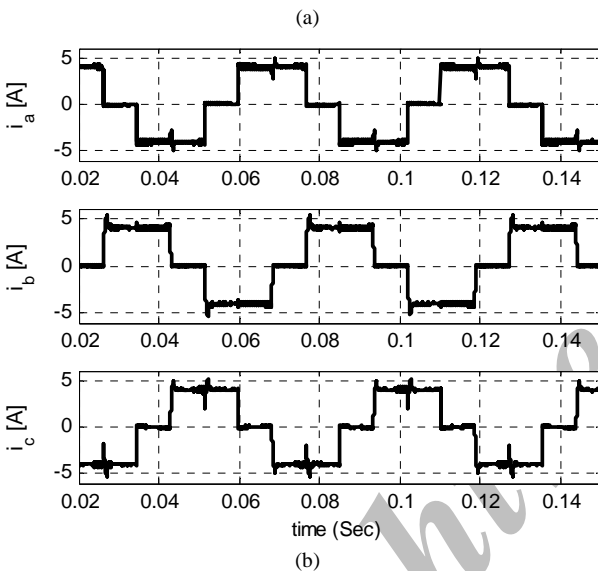


Fig. 10. Circuit schematic of current sensing board.

3) Current Sensing Circuit

To control the speed or torque and also for protection purpose, the instantaneous current must be known. The most common and simplest solution is using low ohmic current sensing resistors in the current path of two phases A and B. But, using resistors causes additional power losses and also has low accuracy. Therefore, Hall Effect current transducers LA55-P have been used and conditioning board has been designed to apply their output to ADC channel of DSP board. Conditioner amplifies and adds DC offset to make the signal between 0~3.3 V. Fig. 10 shows the schematic of the current sensing board.

4) Voltage Sensing Circuit

The developed sensorless control technique is based on the measured voltages  $V_{ao}$  and  $V_{bo}$ . Using resistor voltage dividers is a less expensive and simple way to monitor the voltages. But to isolate the power ground from control ground, proper devices such as linear opto-coupler IL300 must be used. In this paper, Hall Effect linear transducer LV25-P is used that measures the power voltage and isolates it from control ground. Two active second order low pass filters are used to eliminate high frequency

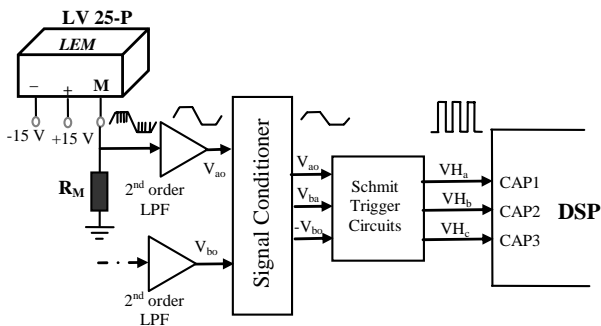


Fig. 11. Circuit schematic of zero crossing detection board.

switching noises. It is required to detect the zero crossing point of the line voltages. Zero crossing detection of the line voltages can be implemented in the software. The filtered voltages after converting to range 0~3.3 V, are applied to DSP without any processing and so, the hardware design is less. Second solution is that the line voltage are made via hardware and then their zero crossing are detected via Schmitt-trigger circuits outside of DSP and virtual hall effect sensors are applied to CAPTURE pins of DSP. Therefore, it is possible to employ the capabilities of CAPTURE unit in EVENT MANAGER of DSP. Fig. 11 shows the schematic of the voltage sensing and zero crossing detection board based on the second solution.

## B. Software Design of the Control System

### 1) Software Organization

This section presents the overall software structure and the interrupt subroutine flowcharts [7]. The software is based on four modules: System initialization, Protection, Startup and the Run modules as shown in Fig. 12(a). The first step for development of the software is to initialize all peripherals on the DSP board, which includes initialization of the PWM ports, timer interrupt, Analog-to-Digital (A/D) converters. Also, the employed variables must be defined in the initialization. The second module checks the healthy of the drive includes power module, DC-link over current, over voltage or other favorite conditions. The third one is the startup procedure for sensorless control. The fourth is the BLDC control dedicated software. It is based on a waiting loop interrupted by both the Timer 2 unit (INT2) and the Capture unit (INT4) of Event Manager A (EVA). The details of each interrupt are shown in Fig. 12 and are explained as following.

### 2) GISR2 General Interrupt Service Routine

Timer 2 interrupt belongs to INT2 level and its request is generated every current loop period with T1 timer period interrupt. As soon as occurrence of this interrupt, general interrupt service routine (GISR2) runs. Fig. 12(b) shows the flowchart control of GISR2. Before running the instructions, drive healthy is checked through protection subroutine. Interrupt operations performed inside are: Start of conversion (measuring the variables that come into ADC unit), speed/torque/current regulation, updating two duty cycles  $D_a$  and  $D_b$ , load the compare registers and finally outting the commands to switch drivers through SEQUENCE subroutine. T1PR register is set to 750 to have 15 kHz current loop frequency. For current regulation, hysteresis controllers are used. At the end of

GISR2, program jumps to infinite loop and waits for the next interrupts.

### 3) GISR4 General Interrupt Service Routine

Capture interrupt belongs to INT4 level and its request is generated whenever a virtual Hall sensor's transition occurs on the each input pins of Capture unit 1 (CAP1, CAP2, CAP3). At its corresponding general interrupt service routine (GISR4), firstly the drive healthy is checked as shown in Fig. 12(c). GP Timer 2 is the time base of Capture unit. The value of GP timer 2 is counted and stored in the corresponding registers when a specified transition is detected on a capture input pin (CAPx). Then, capture pins are configured as GPIO functionality to read the virtual hall sensors states and the rotor position is identified.

### 4) Startup Procedure

Sensorless control schemes are not self-starting. Open-loop starting is a practical way to run the BLDC motor without position sensors that is accomplished by providing a rotating stator field with a certain increasing frequency profile [8]. However, this method must be started from a known initial rotor position. The forced alignment of the motor is a way of setting an initial position. In this paper, after energizing two phases A and B (mode 2) for enough time to ensure the rotor locks into position (mode 3), the next commutation signal advancing the switching pattern by electrical  $60^\circ$  is given. Whenever the motor speed increases enough, the proposed sensorless method can be run.

## IV. EXPERIMENTAL RESULTS

The experimental test bed has been designed and implemented in the laboratory as shown in Fig. 13. The IGBTs are used as inverter switches and the switching frequency is 15 kHz. DC bus voltage is set to 60 V. Fig. 14 shows the phase back EMF voltages of the BLDC motor drive and physical Hall Effect sensor where they are trapezoidal shaped. Rising edge of each position Hall Effect sensor is corresponding to flat part of phase back EMF voltage.

Figure 15 shows the phase current waveforms without using direct phase current (DPC) control method. At this step, physical position Hall sensors have been used. The currents are regulated similar to the current regulation method that is used in six-switch inverter topology. The current of phase A is just controlled and current regulation of phase B is dependent to the regulator of phase A. It can be seen that back EMF voltage of phase C disturbs the currents of phases B and C.

Fig. 16 shows the phase voltages  $V_{ao}$  and  $V_{bo}$  and their filtered waveforms. Here, Duty cycles of the switches are 100% and PWM waveforms on terminal voltages are due to using the DPC method. Higher applied voltage to the motor during two modes 2 and 5 leads to lower duty cycle at these modes. Low pass filters must be tuned well, so that eliminates high frequency PWM waveforms at a wide speed range.

In Fig. 17 the line voltages at 210 rpm have been shown, so that their zero crossing points (ZCPs) are synchronized to commutation instants. These voltages are made using hardware circuits. Estimated (virtual) Hall effect sensors



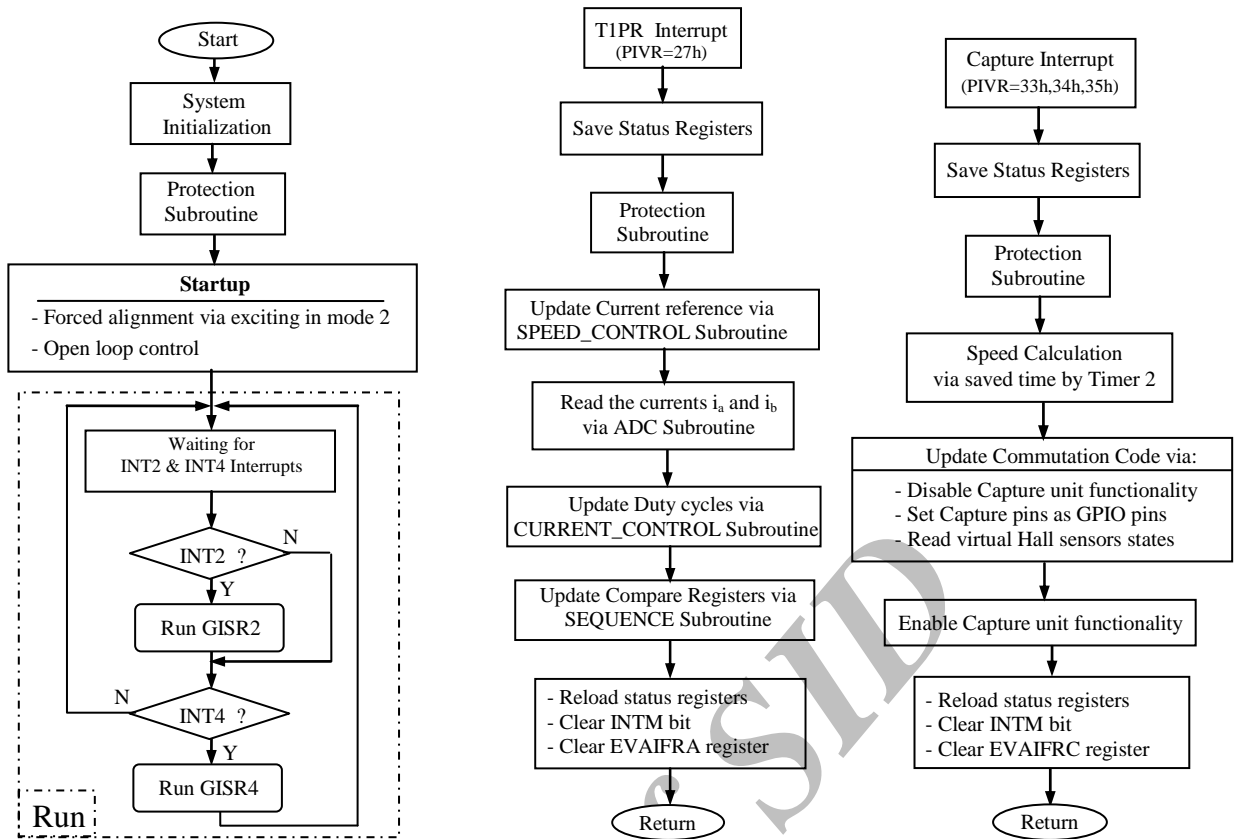
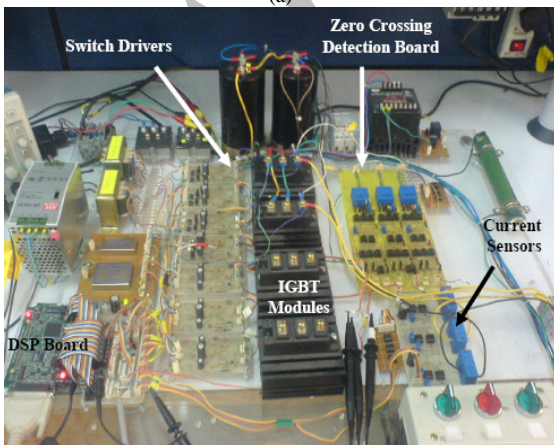


Fig. 12. Control flowcharts of the system software, (a) Main flowchart of system software, (b) GISR2 Interrupt service routine, and (c) GISR4 Interrupt service routine.



(a)



(b)

Fig. 13. BLDC motor drive system setup, (a) Entire of the drive and (b) Main board of the inverter.

signals ( $VH_x$ ) that are synchronized to ZCPs of line voltages are shown in Fig. 18. As shown,  $VH_x$  are

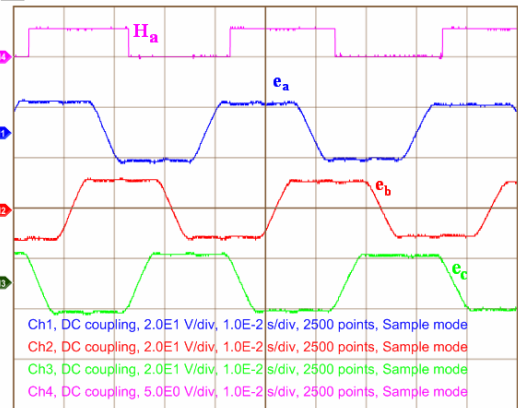


Fig. 14. Measured back EMF voltages and position Hall effect sensors signals of BLDC motor.

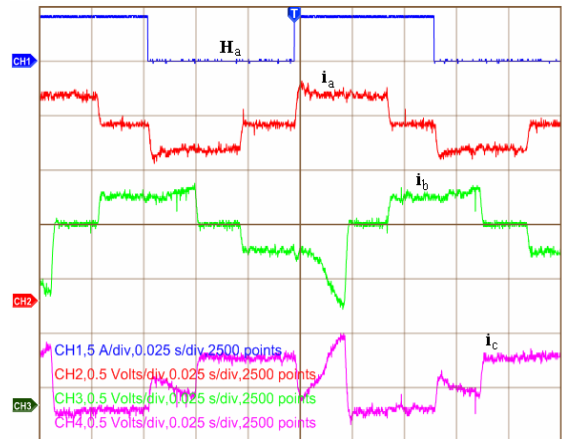


Fig. 15. Phase current waveforms without using DPC control method.

synchronized to the physical Hall Effect sensors signals ( $H_x$ ) and they are in  $120^\circ$  together.

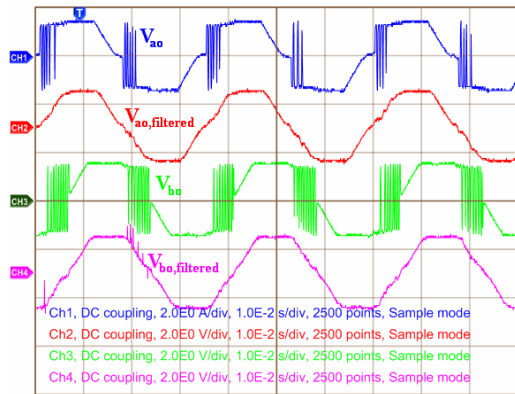


Fig. 16. Terminal voltages  $V_{ao}$  and  $V_{bo}$  and their filtered waveforms.

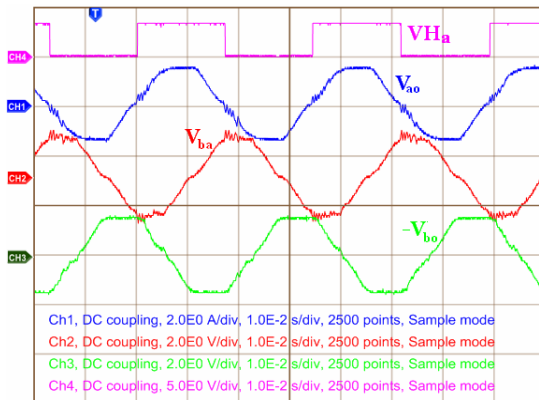


Fig. 17. Developed three line voltages for proposed sensorless control.

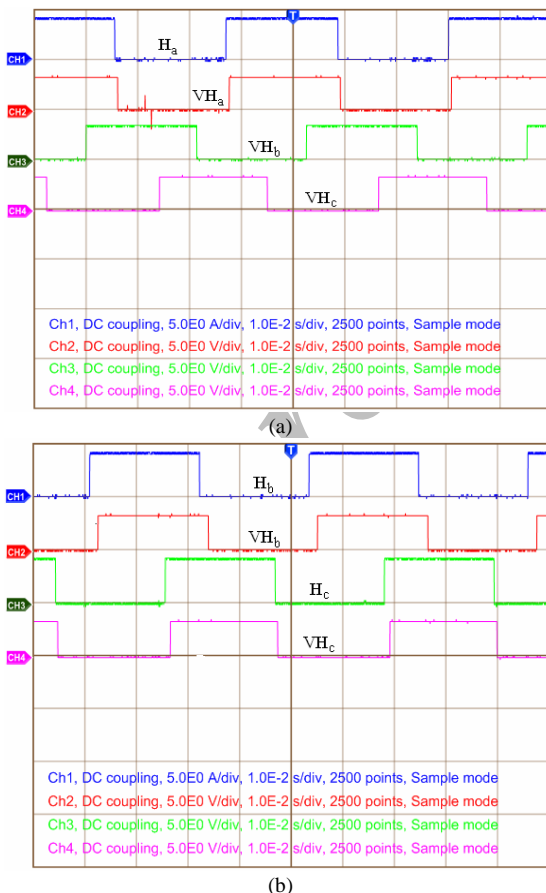
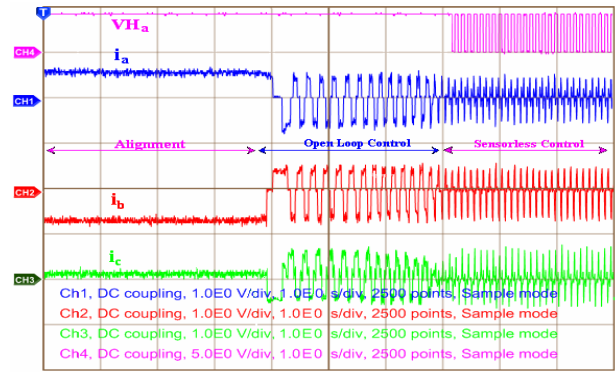
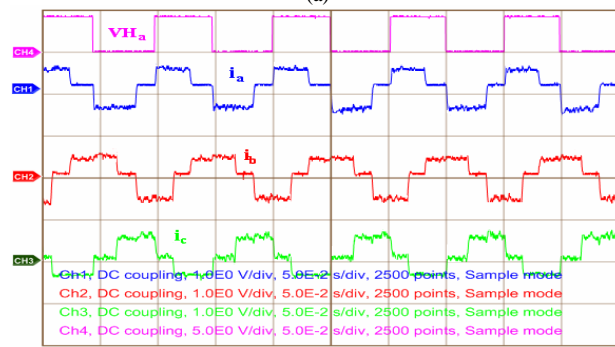


Fig. 18. Relation between virtual (estimated) and physical Hall Effect sensor signals, (a) Relation between  $H_a$  and  $V_{H_{a,b,c}}$  and (b) Relation between  $H_{b,c}$  and  $V_{H_{b,c}}$ .

Phase currents waveforms at startup and steady state using virtual Hall Effect signals are shown in Fig. 19.



(a)



(b)

Fig. 19. Phase current waveforms using virtual Hall signals, (a) Motor startup and (b) Phase current waveforms at steady state.

Current regulation using virtual signals and employing the direct phase current control method is successful and confirms the theoretical results.

Like to other sensorless methods, the voltage filtering and inaccuracy of the measurements lead to some estimation errors of commutation instants that could lead to some torque ripple. The maximum phase delay caused by low pass filters at 210 rpm is  $5.5^\circ$  that is negligible. Moreover, there is an inherent phase delay between zero crossings points of line-to-line voltages and commutation points. It's because of that the commutation points are exactly coincide to line back EMF voltages whereas employed line-to-line voltages lag a bit from the line back EMF voltages due to drop voltage on the stator impedance.

This phase delay depends to the load and stator impedance. At low speeds and for heavy load, this error increases. Therefore, the proposed sensorless method is suitable for applications that their load is increasing as long as the speed increases such as fans and blowers.

### V. CONCLUSIONS

The driving system of a reduced parts BLDC motor drive which can be used in low cost applications was studied in this paper. The control core of the driving system is a TMS320F2407A chip. The main benefits are increased system reliability and cost reduction of the overall system.

Cost reduction is achieved via reducing number of power switches and related circuits such as power supplies and drivers and also elimination of position hall effect sensors. Unlike conventional back EMF based sensorless methods that focus on detection of ZCP of the terminal voltage to neutral voltage, this study proposes a novel sensorless commutation method based on the line voltage. Experimental results confirm the proposed theoretical

analysis and simulation results. The proposed method has several advantages, including the following:

1) Elimination of the motor neutral voltage: The neutral voltage is not required in the proposed method; only the two stator terminal voltages need to be detected.

2) Elimination of the phase shift circuit: The proposed line to line voltages inherently lag 30 electric degrees compared with the phase back EMF voltages.

3) Low starting speed: Since the amplitude of the line voltage is significantly larger than back EMF voltage, a small back EMF can be effectively detected. Namely, a lower open loop starting speed can be achieved (In this study, the lower achievable speed is 40 rpm).

Consequently, the reduced parts inverter is particularly suitable for cost sensitive applications such as home appliances and related computer peripherals.

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**Abolfazl Halvaei Niasar** was born in Kashan, Iran in 1974. He received his B.Sc., M.Sc., and Ph.D. in 1998, 2000, and 2008 from Isfahan University of Technology (IUT), university of Tehran (UT) and Iran University of Science and Technology (IUST) all in electrical engineering respectively.

He is currently with the Department of Electrical Engineering, at University of Kashan. His research interests are mainly PM and Brushless DC motor drives, sensorless drives, DSP based control systems and the industrial control systems. Dr. Halvaei is a member of the Institute of Electrical and Electronics Engineers (IEEE).

**Abolfazl Vahedi** was born in Tehran, Iran in 1966. He received his B.S., M.S. and Ph.D. in 1989, 1992 and 1996 from Ferdowsi Mashhad University, Institut Nationale Polytechnique de Lorraine (INPL-FRANCE) and INPL all in electrical engineering respectively. He has directed several projects in the area of conventional and special electric machines and drives. His research interests are mainly design, implementation and optimization of electric machines including traction motors and drives. He is a member of Center of excellence for power system automation and operation at Iran University of Science and Technology (IUST). He is also a member of IEE and SEE.

**Hassan Moghbelli** was born in Isfahan, Iran in 1950. He received his B.S., M.S., and Ph.D. in 1973, 1978, and 1989 from Iran University of Science and Technology (IUST), Oklahoma State University, and University of Missouri-Columbia (UMC) all in electrical engineering, respectively. He has directed several projects in the area of electric drives, power systems, electric vehicles, hybrid electric and fuel cell vehicles, and railway electrification. His research interests are electric drives, power electronics, and design of electric and hybrid electric vehicle. Dr. Moghbelli is a member of IEEE, ASME, and SAE.